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Assessment of Condition and Decay of Wooden Mats Used in the Construction Industry

With a Review of State-of-the-Art Wood Condition Assessment Techniques

Rubin Shmulsky
Laya Khademibami
Robert J. Ross
C. Adam Senalik
Kevin W. Ragon
Brian K. Brashaw

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Abstract

Wood (or timber) mats are portable and temporary modular platform assemblies that spread short duration heavy loads from construction equipment out across large areas, protecting the environment from rutting and erosion. They are used throughout the United States and around the world. These assemblies facilitate access to construction sites and provide stable working surfaces during infrastructure and construction projects. Some examples of these types of projects include dragline operations, pipe- and transmission-line building and rebuilding, wind and cellular tower construction, crane and heavy lifting for construction, oil field exploration, and temporary bridging across waterways. During their service lives, mats may get used at multiple projects with significant movement, handling, and storage between each use. Given the high load levels and extreme environmental conditions associated with mat use, assessing the condition of these mats during their service life is vitally important for safety and productivity at the construction site. To do this, basic assessment techniques are needed. To that end, the USDA Forest Service, Forest Products Laboratory, and Mississippi State University are working jointly to develop an inspection procedure that is comprehensive, fast, and portable. As a first step toward developing this procedure, this report provides a summary of background information on common engineering properties of wood and how they are affected by decay and deterioration mechanisms, basic techniques for wood condition assessment, and a section on current state-of-the-art inspection techniques, with an emphasis on those potentially applicable to wood mats.

Keywords: wood, access mats, wood mats, working platforms, timber assemblies, deterioration, inspection, in-field assessment

Contents

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USDA Forest Service, Forest Products Laboratory
One Gifford Pinchot Drive, Madison, WI, USA 53726
(608) 231-9200
SM.FS.MailroomFPL@usda.gov

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Assessment of Condition and Decay of Wooden Mats Used in the Construction Industry

With a Review of State-of-the-Art Wood Condition Assessment Techniques

Rubin Shmulsky, Professor and Department Head
Laya Khademibami, Assistant Research Professor
Department of Sustainable Bioproducts, Mississippi State University, Mississippi State, Mississippi, USA

Robert J. Ross, Supervisory Research General Engineer (retired)
C. Adam Senalik, Research General Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

Kevin W. Ragon, Assistant Extension Professor
Department of Sustainable Bioproducts, Mississippi State University, Mississippi State, Mississippi, USA

Brian K. Brashaw, Assistant Director
USDA Forest Service, State, Private, and Tribal Forestry, Cooperative Forestry, Washington DC, USA

Introduction

Wood (or timber) mats are industrial assemblies that spread short-duration heavy loads out across large areas. Using these mats reduces pressure on the ground. This is particularly important for relatively loose soils. By spreading heavy loads across larger areas, environmental impacts such as rutting and soil compaction are minimized. Using these mats contributes to the safe use of heavy equipment, the transportation and staging of construction materials, and ultimately the development of major civil infrastructure projects. Wood mats are used in road construction, waterways maintenance, energy development and transmission, and more. Wind energy and communication tower construction, building and rebuilding of transmission lines, and bridge and pipeline construction are just some of the many direct applications for mats. The majority of mats are constructed of hardwood species, although softwoods species are also used to a lesser extent.

Bolted timber mats (Fig. 1) and three-ply mats (Fig. 2) are the most prominent types of wood mats. Each has unique properties and uses.

The basic constituent material of bolted timber mats is repetitive heavy timbers. These mats generally range from 6 to 12 in. (152.4 to 304.8 mm) thick, from 4 to 8 ft (1.22 to 2.44 m) wide, and from 14 to 40 ft (4.27 to 12.20 m) long. In addition to rough green lumber, often used for beams and stringers or posts and timbers, other materials such as glue-laminated timber (glulam) or other structural composites

Figure 1—Timber mats that have been broken in flexural testing (8 in. (0.2 m) thick by 24 in. (0.6 m) wide by 14 ft (7.3 m) long). Used with permission from Mississippi State University.

Figure 2—Three-ply oak mat (made from nominal 2- by 8-in. (standard 38- by 184-mm) planks) that has been cut into 2-ft-wide specimens prior to flexural testing. Used with permission from Mississippi State University.

may be used as constituent billets. The constituent timbers are held together with repetitive steel tension rods along the length of the assembly. The redundant rod spacing varies among mats and producers but is generally from 2 to 5 ft (0.61 to 1.52 m). Bolted mats are stiffer and stronger than three-ply mats because of their thick sections, parallel laminated construction, and repetitive members. Structural grading of the constituent timbers can be performed. Bolted mats are commonly used for heavier and more critical load applications, such as crane operations.

Three-ply mats are made from multiple planks of wood that are cross-laminated (cross-laminated timber (CLT)). Typically, constituent lumber is approximately 2 by 8 in. (50.8 by 203.2 mm) in cross section and ranges from 12 to 16 ft (3.66 to 4.88 m) long. The mats typically finish at 8 ft (2.44 m) wide by 12 to 16 ft (3.66 to 4.88 m) long. Planks may be applied edge to edge (solid face) or with gaps between adjacent members (waffle face). Nails, bolts, screws, other mechanical fasteners, or some combination of these are used for assembling the three cross-laminated plies. Adhesively bonded kiln-dried lumber (CLT) is a relative newcomer to matting applications. Three-ply mats are intended for lighter load applications. Because they are typically somewhat flexible, particularly compared with bolted timber mats, they are favored for use in access applications on uneven terrain.

Mats are subjected to extreme use and environmental conditions. Their service lives are relatively short; often on the order of 3 to 10 years. They become mechanically abraded by the grousers on tracked crawlers climbing, operating, and turning on their surfaces and edges. When used as temporary bridging over creeks and streams or as skidder bridges, they are subjected to short duration but very large flexural stresses. Often they are dragged over rocky and/or muddy terrain to be installed as an access road or laid down or picked up as a working pad. They may spend much of their service life in the mud or partially submerged as they work to keep equipment upright and out of swampy or marshy soil. They may be lifted with grapples or hooks at the end of one job. When used in swampy conditions, or put into storage thereafter, the wood is subject to deterioration. Deterioration progresses at differing rates and is particularly aggressive in the warm and humid states adjoining the Gulf of Mexico (from Texas to Florida). In the Gulf Coast region of the United States where agents of deterioration are particularly aggressive, service lives of wood-based mats are particularly short.

Species that go into matting products vary. Because mats are locally produced, they are made from whatever species mix is available from the local or regional timber resource base. Although there is no specific limit or species constraint, generally stiffer and stronger materials are more favorable. Major hardwoods include but are not limited to ash, beech, birch, black gum, elm, hickory, maple, red and white oak, sweetgum, and sycamore. Major softwoods include but are not limited to southern pines, Douglas-fir, western hemlock, and western larch.

Mat timbers and planks may be visually evaluated and/or graded. Proprietary grades may be used based on the nature of the timber resource and/or customer needs. Special attention to wane may be important for applications in which ground pressure may be critical.

Mats may be sold to users or wholesalers at the time of manufacture or may be leased or rented. Regardless of the business model, the users and owners always want and need to maximize the service life of the product. Through their respective service lives, mats are often derated. That means that as they go from their maximum utility value state (new) through their service life, biological and mechanical damage reduces their mechanical capacity. They continue to be used albeit in successively less demanding applications. Ultimately, these industrial products are used until they can no longer be shipped, handled, or support loads as intended. Finally, at the end of their life, the mats are typically stripped of metal fasteners and then chipped and burned for energy. Using wood fiber in this manner maximizes forest sustainability and timber resource availability.

Given that the service lives of these products are relatively short (on the order of 3 to 10 years) and their change in flexural capacity is relatively high during that service life, in-field inspection and evaluation techniques are needed. These may range from cursory visual inspections to in-depth nondestructive evaluations. These inspections are increasingly critical given the high load levels associated with heavy crane lifts and other infrastructure development activities.

In addition to visual and other basic in-service inspection methods, significant technical advancements have been made in inspection methods for wood assemblies and structures in recent years. These are covered in a separate section on state-of-the-art-techniques.

The eventual goal of this research effort is to provide a field inspection guide based on state-of-the-art wood inspection technology. As a first step toward this goal, this report provides the following:

- Background information on the engineering properties of wood and deterioration mechanisms that affect wood performance
- A listing of basic techniques that could be considered for assessing wooden mats
- A review of state-of-the-art techniques for wood condition assessment

In-Service Deterioration and Its Effects on Engineering Properties of Wood

Engineering Properties of Wood

Materials that have the same mechanical properties in each direction, such as many metals, plastics, and cement, are termed isotropic. In contrast, wood has drastically different properties parallel to the grain versus perpendicular to the grain, and thus it is termed anisotropic (meaning not isotropic). More specifically, wood can be considered an orthotropic material, that is, one that exhibits different properties in the three mutually perpendicular directions or axes that correspond to the three primary axes of a tree (Shmulsky and Jones 2019). The strength and elastic properties of wood are different in the longitudinal, tangential, and radial directions, although the properties in the radial and tangential directions are often similar. Commonly for each species, the strength properties along (parallel to) the grain are 10 to 20 times greater than the same properties as measured across (perpendicular to) the grain.

In the case of wood mats, several strength properties are critical. Generally, bending strength (F_b) and moment capacity (M) are crucial because a mat serves largely as a beam on an elastic foundation. Bending stiffness (EI) is also important because mats deflect under heavy loads and atop relatively weak soils. The ability to design crane lifts that prevent overturning is often dependent on mat stiffness. In many cases where surface rutting must not exceed quantified limits, for example 3 in. (76.2 mm), deflection may be a limiting factor. Compression perpendicular to grain and horizontal shear are of lesser importance and are not typically limiting factors. But compression perpendicular to grain ($F_{c\ perp}$) is important when loads are very high, for example under crawler grousers or under sheep's-foot compactors. Similarly, horizontal shear (F_v) may be critical in cases where short deep beams are used, such as cases where small mats are used as outrigger pads.

With time, as the utility value of the mat depreciates, the importance of compression perpendicular to grain, shear, and tension perpendicular to grain increases, particularly in combination with respect to fastener holding capacity. These properties are generally not problematic in new, freshly manufactured or otherwise sound mats. As infrastructure projects, structures, and equipment increase in size, the loads applied to mats increase as well. As such, the ability to continually assess the residual capacity in used mats becomes increasingly important.

Effect of Decay on Physical and Mechanical Properties of Wood

The presence of deterioration caused by decay has a significant effect on various properties of timber. The following section provides a summary of the effect decay has on various strength properties of wood. Table 1 summarizes the early scientific literature on estimated values for strength losses in softwoods and hardwoods at early stages of decay.

Toughness

Toughness, or impact bending, is the ability of a wood member to withstand shock loading. It is generally considered to be the strength property most affected from early stages of decay. Research dating to 1954 (Mulholland 1954) indicates a loss of toughness of 50% with a corresponding loss of only 1% in weight.

Static Bending

Static bending properties include modulus of elasticity, modulus of rupture, and work-to-maximum load. Research dating to the 1930s (Cartwright and others 1931, Scheffer 1936) has been conducted on this topic. Reported results indicate a significant loss on modulus of rupture (strength) with decayed wood. Strength tests are the most used method to evaluate the influence of decay on mechanical properties. Through mechanical tests, it is possible to determine if wood, either treated or untreated, has been damaged by biological decay (Ibach and Lebow 2014).

Other Strength Properties

Other strength properties include compression and tension parallel and perpendicular to grain, shear parallel to grain, and tangential hardness. Research has shown that these properties are also impacted by deterioration caused from decay. To develop improved methods for detecting and quantifying the effect of decay fungi on wood products, Nicholas and Janzen (2016) developed a soil block decay test that used perpendicular-to-grain compression properties (modulus of elasticity and strength). They found that early stages of decay were detected in both radial and tangential loading directions. It is significant that compression strength loss was found to be the most sensitive measure of wood decay.

Fundamental Relationships between Physical and Mechanical Properties of Deteriorated Wood

Pellerin and others (1985) were the first to report on a systematic examination of the effect of biological attack on the acoustic properties of clear wood and its relationship to strength. They used small, clear Southern Pine specimens in

Table 1—Estimated values for strength losses in softwoods and hardwoods at early stages of decay (indicated by weight loss) by brown-rot and white-rot fungi as a percentage of the value for nondecayed samples[a,b]

	Strength property loss (%)										
			Static bending								
Approx. weight loss (%)	Toughness	Impact bending	General bending strength	Work to maximum load	MOR[c]	MOE[c]	Compression perpendicular (radial)	Compression parallel	Tension parallel	Shear parallel	Hardness
					Brown rot						
Softwoods											
1	57	20–38	—	—	—	—	—	—	—	2	—
2	—	20–50	5	27	13–50	4–55	18–24	10	23–40	—	—
4	75	25–55	—	—	—	—	25–35	—	—	6	7
6	—	62–72	16	—	61	66	48	25	60	—	—
8	—	78	—	—	—	—	48–60	—	50	15	21
10	—	85	36	—	70	—	66	45	—	20	—
Hardwoods											
1	–	6–27	—	—	—	—	—	—	—	—	—
2	36	31–50	—	54	32	—	6–10	—	56	—	—
4	—	60–70	—	69	49	—	—	—	—	—	—
6	—	80	—	75	61	—	16–25	—	—	—	—
8	—	9–89	13–34	—	—	—	19	—	82	—	—
10	60	70–92	—	—	—	—	—	—	—	—	—
					White rot						
Softwoods											
1	55	—	—	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	10–20	—	4–38	—	—
4	—	—	—	—	—	—	—	—	8–43	—	—
6	75	—	—	—	—	—	32–61	—	10–49	—	—
8	—	—	—	—	—	—	—	—	14–58	—	—
10	85	—	—	—	—	—	—	—	20–63	—	—
Hardwoods											
1	—	21	—	—	—	—	4	—	—	—	—
2	—	26	—	28–35	13–14	4	5	—	22–42	—	—
4	70	44	—	38	20	—	—	—	17–44	—	—
6	75	50	—	45–53	20–27	10	12–27	14	12–58	—	18
8	—	—	—	—	—	—	—	—	14–49	—	—
10	85	60	—	58	24	14	35	20	20–50	—	25

[a] From Wilcox (1978). Values obtained from published experimental results and adjusted to equivalent weight loss levels.

[b] Sources: Brown (1963), Cartwright and others (1931), Gillwald and Michalak (1963), Hartley (1958), Henningsson (1967), Kennedy (1958), Kennedy and Ifju (1962), Kubiak and Kerner (1963), Mizumoto (1966), Mulholland (1954), Pechmann and Schaile (1950), Richards (1954), Scheffer (1936), Toole (1971), and Wilcox (1968).

[c] MOR, modulus of rupture; MOE, modulus of elasticity.

a laboratory study designed to examine the effect that brown-rot decay fungi and termite attack had on acoustic velocity and static strength. Time-of-flight measurements were made parallel to the fiber axis using a pitch and catch system on specimens after various exposure times. They observed a considerable change in acoustic time-of-flight with exposure time. More importantly, they were able to conclude the following:

- Changes in time-of-flight occurred well before measurable weight loss (density) and strength loss were observed.
- A significant correlation was observed between residual strength and acoustic time-of-flight.
- Because termite attack was preferential to the early wood sections of the specimens, time-of-flight measurements parallel to the fiber axis were not useful for monitoring changes in corresponding strength.

In follow-up studies, DeGroot and others (1994, 1995, 1998) examined both the energy storage and loss parameters for clear wood during deterioration by natural populations of decay fungi and subterranean termites. They used a pulse-echo test setup (Ross and others 1994) to measure the speed of sound transmission and wave attenuation, parallel to the fiber axis, in small clear Southern Pine specimens in field exposure conditions. They also developed empirical models that used both parameters and were capable of predicting residual compressive strength with a high level of accuracy (Ross and others 1996, 1997). A similar relationship was reported by Ross and others (2001) for timbers removed from service.

Verkasalo and others (1993) investigated the effect that anaerobic bacterial infection, specifically by *Clostridium* spp. and *Erwinia* spp., had on various properties of red oak wood. Anaerobic bacteria secrete enzymes that are able to degrade pectic substances of the compound middle lamella as well as starch, tannins, and possibly monomeric wood sugars (Schink and Ward 1984, Ward and Zeikus 1980). Consequently, chemical bonds between wood cells are weakened. The degradation is indicated by destroyed pit membranes and microcracks between the cell walls. Thus, although the secondary cell walls appear to remain intact and the wood maintains its original density, the wood's ability to withstand drying stresses is reduced (Ward and Pong 1980). Verkasalo and others (1993) found that the presence of anaerobic bacteria significantly reduced several physical and mechanical properties.

Rutherford and others (1987) examined the relationship between dynamic and static modulus of elasticity values of Douglas-fir samples exposed to brown-rot decay fungi (*Gloeophyllum trabeum*) for exposure times between 2 and 12 weeks. A strong statistical relationship was found to exist.

Basic Techniques for Wood Condition Assessment

Visual Techniques

Visual inspection is the fastest and lowest cost inspection method and is the first step in assessing the condition of wood mats. It has the benefit of identifying obvious problems requiring immediate action. But visual inspection may not reveal to the inspector the internal condition of a mat's constituent timbers or planks. This step identifies features such as missing or damaged components, as well as environmental damage. Figure 3 shows a stack of mats with one in the middle that has a missing steel bolt. When hardware such as this is missing, the load sharing ability of the individual timbers in the mat is reduced.

Environmental damage is primarily from weather exposure, insects, or fungi. Excessive checking can reduce the mat strength and create pathways for agents of decay to get deep into the mat interior. Frass and/or mud tubes indicate the presence of burrowing insects, which may be destroying the mat from the inside out. Thin black lines in the wood (spalting) or spotty bleaching, indicate the early- to mid-stages of decay. When mats are dirty, however, these can be difficult to detect. Conks, sometimes called ears, or the fruiting bodies of fungi, indicate advanced decay. After these appear, the residual strength and stiffness are severely compromised. Figures 4 and 5 illustrate decay on mat members.

Figure 3—Stack of used mats. The mat in the middle exhibits a missing steel rod that would otherwise be holding the constituent timbers together and promoting load sharing. Photo is property of Mississippi State University.

Figure 4—Advanced decay in a mat timber. This level of decay negates the mat's strength entirely. It is ready to be retired, stripped, and recycled. Photo is property of Mississippi State University.

Figure 5—Fungal fruiting bodies on the end-grain of a glue-laminated mat timber. These fruiting bodies indicate advanced decay. The strength of this timber is thus significantly reduced and warrants further inspection and evaluation. Photo is property of Mississippi State University.

Insects and decay can be particularly prominent in warmer climates and in mats that are used in partially submerged (continually wet) situations. These problems are also prominent in mats that are dead stacked, meaning piled without any cross outs or dunnage to separate mats in a stack, which if included, would facilitate airflow and surface drying. Figure 6 shows mats stacked on cross outs to facilitate airflow and drying, which minimizes biological degradation during storage. Stacking with cross outs takes more time and space. But the increase in service life may warrant the extra time and expense.

Mechanical damage is another important characteristic that is generally identifiable by visual observation. Timber breaks, fractured members, broken or bent fasteners, excessively worn corners or edges, all provide clues to the past service life of a given timber mat. Many potential issues identified through visual inspection require additional examination.

Probing Techniques

The technique of probing is often done with a sharp and/or pointed tool such as a knife, awl, or (particularly around the groundline) a sharpened shovel blade or similar long-handled sharpened pick. Probing can identify surface rot on wood mats. By inserting the probe under a small portion of surface wood and lifting, the presence of surface rot can be detected by the nature of the break. Splintered breaking is indicative of sound wood, whereas brittle breaks are indicative of surface rot. Probes can also assess the hardness and toughness of the mat surface. Soft surfaces or the lack of resistance to probe insertion are indicators of decay. The use of a probe for mat assessment is a simple technique but requires the inspector to have knowledge of wood behavior in both sound and decayed conditions. For example, sound, wet wood may appear to be soft and may look like decayed wood. In this case, the inspector would then either need to have experience to decide if the wood was sound or progress to additional assessment techniques.

Probing may also be used to measure the depths of checks and holes and identify the shell thickness of hollowed timbers or the residual thickness of mats with surface degrade. There are several specialized probes made for these purposes: flat probes for measuring check depth, feeler gauges for measuring check width, and shell thickness indicators for finding voids. A shell thickness indicator is a metal rod with a small hook on one end and is often used in conjunction with drilling techniques. The shell thickness indicator is inserted into a hole (normally a drilled hole). If the hole opens into a larger void, such as a hollowed timber, then the hook catches at the point where the hole enters the void. The presence of the void is noted, and the distance of the void from the surface of the timber is measured.

Figure 6—New 3-ply CLT mats (left) and used bolted mats (right). The used mats are staged for deconstruction and reconditioning in which the good timbers will be reassembled and again used as mats and the broken timbers will be chipped for fuel. In each photo, the individual mats are separated by cross outs (sticks or other dunnage) to facilitate both handling and airflow. Both photos are property of Mississippi State University.

Sounding Techniques

A sounding test is performed by striking the wood member with a blunt object such as a heavy hammer. The inspector determines the likely presence of rot by both the feel of the hammer at impact and the resulting sound of the impact. A hollow sound or damped “thud” are indicative of internal decay. Comparatively, a sharper, ringing sound is indicative of sound wood. Sounding will often reveal advanced decay or hollowed centers but is unlikely to reveal incipient or moderate decay. To be effective, a relatively heavy hammer (3–4 lb (1.36–1.81 kg)) or larger sledgehammer (7–8 lb (3.18–3.63 kg)) must be used for larger materials. Also, the interpretation and effectiveness of sounding is dependent upon the experience of the inspector.

Drilling Techniques

Sudden decreases in resistance during drilling or coring are indicative of voids or areas of rot. If a defect is detected, then a shell thickness indicator is used to measure the distance from the surface of the mat to the defect region. A shell thickness indicator is a thin rod approximately the thickness of the corer or drill used to make the hole. It has a slight hook on the end that enables the inspector to determine the location of the edge of the defect. If a defect is identified after drilling or coring, then additional holes should be drilled in the vicinity to estimate the size of the defect. After the defect size is estimated, then a decision can be made regarding treatment, reinforcement, or replacement.

Estimating Remaining Service Life

One of the criteria for estimating residual strength and stiffness is depth of a mat. Strength is a square function, and stiffness is a cubic function related to depth. Thus, as a mat becomes thinner with time due to wear and tear, abrasions, cutting, decay, or other reasons, the mat quickly becomes weaker and deflects more under any given load.

Figures 7 and 8 show theoretical residual strength and stiffness, respectively, as a function of residual depth, of an exemplar 8-in.- (0.2-mm-) deep timber or timber mat. These figures show that a small reduction in timber depth leads to large reductions in strength and stiffness. In this case, residual depth, in percentage, is calculated as minimum depth (at the time of measurement) divided by initial depth (at the time of manufacture).

Another means of strength and stiffness loss comes from wane (missing wood) or abrasion at corners or edges. With time in service, mat corners become abraded from movement, handling, dragging, crawler grousers, etc. In addition to reduced strength and stiffness, wane and rounding of corners reduce surface contact area, and thereby increase contact pressure and potential deflection and sinking. Figure 9 compares the strength and stiffness of a square section timber with one that’s become rounded at one edge over time.

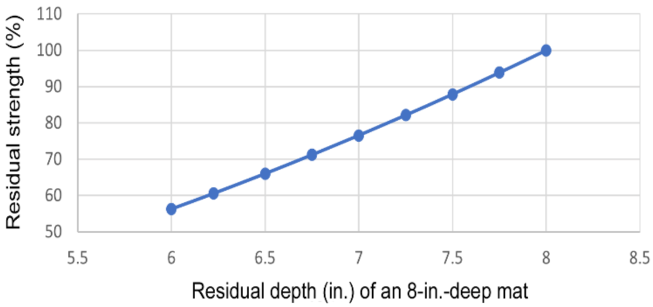


Figure 7—Estimated bending strength loss as a function of residual depth of an 8-in.- (0.2-m-) deep mat. In this case, a loss of approximately 1 in. (25.4 mm) of depth reduces strength by approximately 25%. Strength is proportional to section modulus, and section modulus is proportional to thickness squared: $Z = bh^2/6$ (Cheng 1997, p. 491). Image is property of Mississippi State University.

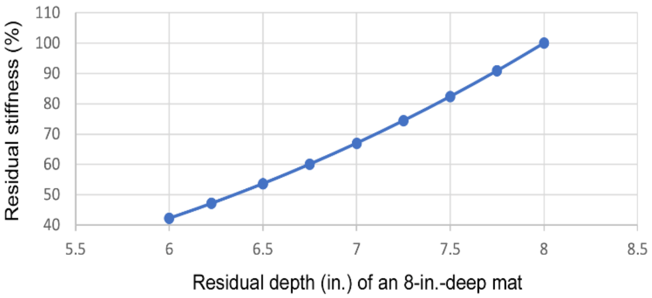


Figure 8—Estimated bending stiffness loss as a function of residual depth of an 8-in.- (0.2-m-) deep mat. In this case, a loss of approximately 1-in. (25.4-mm) of depth reduces stiffness by approximately 33%. Stiffness is proportional to moment of inertia, and moment of inertia is proportional to thickness cubed: $I = bh^3/12$ (Cheng 1997, p. 300). Image is property of Mississippi State University.

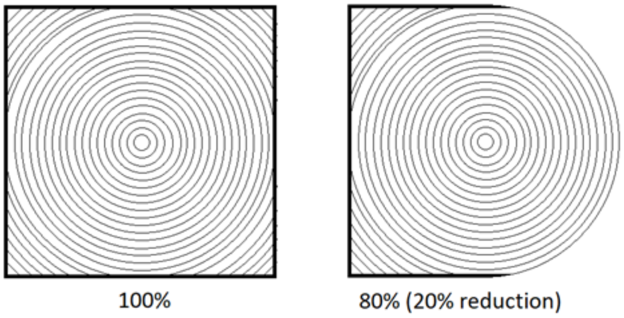


Figure 9—Freshly machined (left) and heavily abraded or worn (right) mat timbers. The rounding and reduction in cross section of the worn timber leads to significant strength and stiffness loss, in this case approximately 20%, particularly for timbers at the edges of mats. Image is property of Mississippi State University.

State-of-the-Art Wood Condition Assessment Techniques

Forest Products Laboratory and Mississippi State University scientists are frequently asked for assistance on the condition of in-service wood and wood products in historic artifacts and structures (Ross and others 2006). The *Wood and Timber Condition Assessment Manual: Second Edition* (White and Ross 2014) and *Nondestructive Evaluation of Wood: Second Edition* (Ross 2015) provide excellent background information on assessing condition of wood, including nondestructive techniques.

A number of publications exist on the use of these techniques in specific inspections that were conducted (Allison and others 2008; Clausen and others 2001; Emerson and others 2002; Franca and others 2015; Ross and Dundar 2012; Ross and Wang 2005; Ross and others 1998, 2017; Wang and others 2008). These publications provide useful information on the application of wood condition assessment techniques.

The Forest Products Laboratory and cooperators have also prepared a number of guides for use of these techniques and interpretation of results obtained from them (Brashaw and others 2005a,b; FPL 2000; Ross and others 1999).

Resistance Microdrilling

Another commercially developed drilling technique is the resistance drill system. Developed in the late 1980s, this system was originally designed for use by arborists and tree care professionals to assess tree rings, evaluate the condition of urban trees, and locate internal voids and decay. This technology is now being used to identify and quantify decay, voids, and termite galleries in wood beams, columns, poles, and piles. This technique is now the preferred drilling technique for timber elements. Figure 10 shows a resistance microdrill being used to assess the level of decay in a historic log cabin.

Figure 10—A resistance microdrill being used for inspection of a historic Civilian Conservation Corps log cabin.

Several machine types are available from different manufacturers. They operate under the same general principle of measuring electrical power consumption of a needle rotation motor. This value is proportional to mechanical torque at the needle and primarily depends on wood density. The purpose of the equipment is to identify areas in timber elements that have low density, indicating decay or deterioration.

Resistance drill equipment measures the resistance of wood members to a 0.6-in.- (1.5-mm-) diameter drill bit with a 0.18-in. (3.0-mm) head. This flat-tipped drill bit travels through the member at a defined movement rate and generates information that allows an inspector to determine the exact location and extent of any damaged area. Figure 11 shows several drill bit ends that are used in resistance drilling. Although the unit is usually drilled into a member in a direction perpendicular to the surface, it is also possible to drill into members at an angle (Fig. 12).

Figure 11—Flat-tipped resistance drill bits used to inspect timber materials.

Figure 12—Drilling can be done at an angle to assess the area below the ground line.

Resistance drills collect data electronically and can also produce a chart or printout showing relative resistance across the drilling path. Modern tools are also promoting the ability to view the data on a tablet computer or mobile phone. Areas of sound wood have various levels of resistance, depending on the density of the species. However, voids produce no resistance. The inspector can determine areas of low, medium, and high levels of decay with this tool and can quantify the level of decay in the cross section. Figure 13 shows a timber abutment cap being assessed with a resistance microdrill and the resulting chart image, which shows minimal drilling resistance and indicates that the majority of the cap is decayed. Figure 14 shows a commercial model with an electronic display that allows data to be reviewed in the field and then further processed using a computer in the office. All holes should be filled after drilling, especially if no decay is present. For the microdrill, this can be accomplished by injecting a small

Figure 13—Resistance microdrilling showing significant decay in the bridge pile cap. The inlay shows the paper chart readout from a commercial drilling unit. This technique can be readily applied to mats and timber bridge structures.

Figure 14—Electronic display on a resistance drill in use.

amount of silicone sealant or marine adhesive into the small opening (Fig. 15).

Interpreting Drilling Data Charts

Charts or printouts should be reviewed in the field and notes taken to ensure understanding of the testing location. Notes should be taken on a graphical data chart. Care should be exercised to ensure that low density profiles from intact but soft wood (such as conifers or relatively low density hardwoods) not be misinterpreted as decay. The very center of many softwood species near the pith will have low resistance and lack the defined growth rings visible in the outer sections. It is important to understand the type of wood that is being drilled. Sound wood from many hardwood species may have high levels of resistance (greater than 50%), whereas sound wood from softwood conifers may have low levels of resistance (in the range of 15% to 50+%, depending on its inherent density). It is important to evaluate the levels of decay across the full dimension because some species have low drill resistance values but are not decayed. Further, each piece of commercial equipment provides different scales and may indicate different resistance levels. Example electronic drilling charts for a southern yellow pine pile and a Douglas-fir pile cap are shown in Figures 16 and 17, respectively. Note that although the fundamental concept of these pieces of equipment is essentially the same, data analysis and subsequent display of the data can vary significantly, depending on equipment manufacturer.

Figure 15—Silicone is used to fill the small drilling hole.

Stress-Wave-Based Techniques

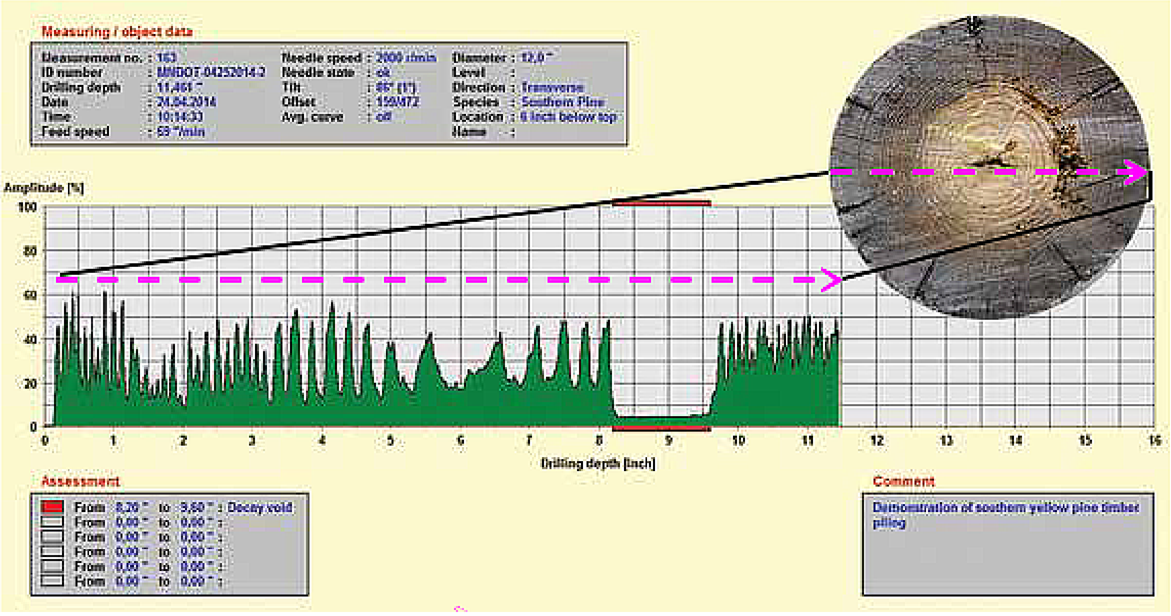
As an introduction, a schematic of the stress wave concept for detecting decay within a circular wood member is shown in Figure 18. First, a stress wave is induced by striking the specimen with an impact device (such as the hammer shown in the illustration). The specimen is instrumented with an accelerometer that emits a start signal to a timer. A second accelerometer, which is held in contact with the other side of the specimen, senses the leading edge of the propagating stress wave and sends a stop signal to the timer. The elapsed time for the stress wave to propagate between the accelerometers is displayed on the timer.

The velocity at which a stress wave travels in a member is dependent on the properties of the member only. All commercially available timing units, if calibrated and operated according to the manufacturer's recommendations, yield comparable results.

The use of stress wave velocity to detect wood decay in timber bridges and other structures is limited only by access to the structural members under consideration. This technique is especially useful on thick timbers, mats, or glulam timbers ≥3.5 in. (≥89 mm) where hammer sounding is not effective. Access to both sides of the member is required. Given their portable nature, mats are easy to access on both sides.

An impact to the end grain of a beam or post will cause a primarily longitudinal stress wave along the length of the cell structure in the timber. An impact to the side or top of the beam will cause a wave across or transverse to the wood cells. Cells are arranged in rings around the center of the tree. The velocity at which a stress wave propagates in wood is a function of the angle at which the fibers of wood are aligned (which is also a determinant of other physical and mechanical properties). For most structural members, fibers of the wood align more or less with the longitudinal axis of the member.

Stress wave transmission times are shortest along the grain (with the fiber) and longest across the grain (perpendicular to the fiber). For Douglas-fir and Southern Pine, stress wave transmission times parallel to the fiber are approximately 60 μs/ft (200 μs/m). Stress wave transmission times perpendicular to the fiber range from 259 to 305 μs/ft (850 to 1,000 μs/m). Researchers have determined that the longest transverse-to-grain transmission times are found at a 45° orientation to the annual rings. The shortest transmission times are about 30% faster in a path that is radial (Fig. 19). These values can vary ±10% for species variation. These times are based on an assumed stress wave



Measuring / object data

Measurement no. : 163
ID number : MNDOT 04252014.2
Drilling depth : 11,461 "
Date : 24.04.2014
Time : 10:14:33
Feed speed : 59 "/min
Needle speed : 2000 r/min
Needle state : ok
Tilt : 86° (1°)
Offset : 159/472
Avg. curve : off
Diameter : 12,0 "
Level :
Direction : Transverse
Species : Southern Pine
Location : 6 inch below top
Name :

Assessment

🟥 From 8,20 " to 9,60 " : Decay void
☐ From 0,00 " to 0,00 " :
☐ From 0,00 " to 0,00 " :
☐ From 0,00 " to 0,00 " :
☐ From 0,00 " to 0,00 " :
☐ From 0,00 " to 0,00 " :

Comment

Demonstration of southern yellow pine timber piling

Figure 16—Electronic view of a southern yellow pine timber piling showing a decay pocket between 8 and 10 in. (0.2 and 0.25 m) of the drilling profile.

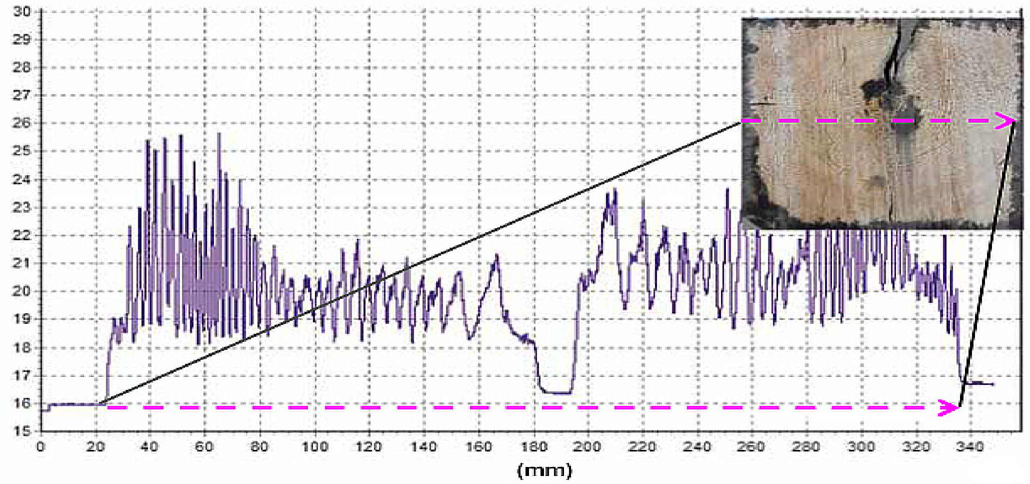


Figure 17—Electronic resistance chart of a Douglas-fir pile cap showing a large crack between 7.09 and 7.87 in. (180 and 200 mm) along the drilling path.

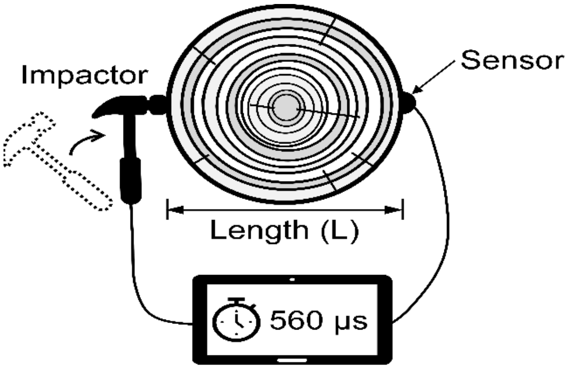


Figure 18—Stress wave timer.

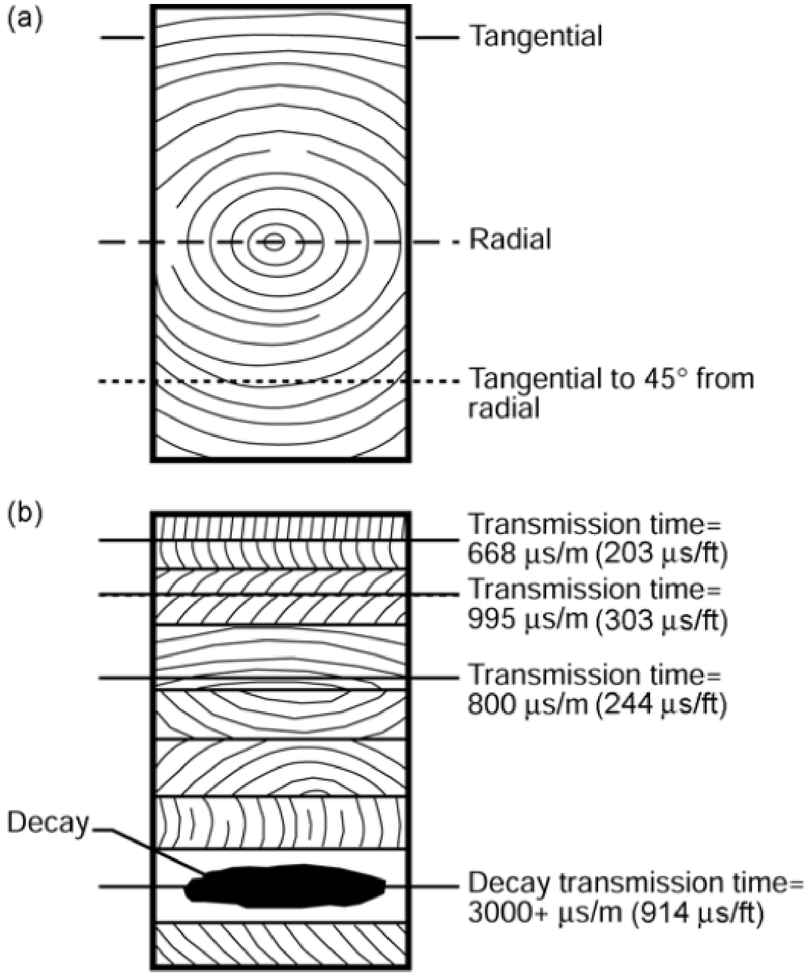


Figure 19—Transverse stress wave paths and transmission times: (a) solid timber; (b) glulam beam.

transmission time of 203 µs/ft (668 µs/m) radially, 244 µs/ft (800 µs/m) tangentially, and 303 µs/ft (995 µs/m) at 45° to grain. Figure 19 illustrates the use of stress wave transmission for heavy timbers such as those used in mats.

Acoustic Signal Analysis

Acoustic signal analysis builds upon the existing acoustic techniques. A piezoelectric transmitter and receiver are placed on either side of a round pole (Lee and others 2020). One generates a signal that passes through the pole and is received by the other. Acoustic signal analysis capitalizes on the known shape of the pole and cylindrically orthotropic wave behavior to predict how stress waves move through sound wood. The entire received signal is used in the analysis. Parameters examined include time of flight, energy loss, and attenuation rate. Deviations from known parameters are indications of internal defects such as voids or decay. The inspection is fast and can differentiate between shell decay and center decay. This method is a black box solution as the user must rely on the internal algorithm of the device. Also, although this technique has been used successfully on round timbers, its use in square members is still under investigation (Lee and others 2020).

Laser Scanning

Three-dimensional (3D) laser scanners are instruments that record precise and accurate surface data of objects in a nondestructive manner. These instruments use a beam of infrared light to calculate and record the distance to an object, typically as data points with spatial coordinates. These data are then analyzed using various types of computer software to generate a detailed image of coordinates and dimensions. Three-dimensional laser scanners have been used successfully to digitize objects of various sizes ranging from small diagnostic artifacts to large, complex sites of monumental architecture.

A number of companies manufacture various types of 3D laser scanners. Generally, these units use light detection and ranging technology (LiDAR), where laser pulses determine the distance to an object or surface. The distance to an object is determined using time-of-flight between transmission of a pulse and detection of the reflected signal. A point cloud of data is then collected and can be converted into the true shape of the object.

A laser beam is emitted from a rotating mirror toward the area being scanned. The laser beam is then reflected back to the scanner by objects in its path. The distance to the objects defining an area is calculated, as well as their relative vertical and horizontal angles. Figure 20 shows a laser scanner being used to inspect a historic covered bridge.

Several types of images can be presented from processing point cloud data including a point cloud image resulting from only one scan, a point cloud image created from multiple scans, a parametric picture created from a point cloud scan, a point cloud image imbedded in AutoCAD, and 2D/3D AutoCAD images.

Use of laser scanning technologies for inspection of wood structures has been investigated. In a study conducted by University of Minnesota Duluth's Natural Resources Research Institute (UMD NRRI); USDA Forest Service, Forest Products Laboratory; and the U.S. Department of Transportation, Federal Highway Administration, laser scanning technologies were used to provide as-built records for historic covered timber bridges. Detailed documentation of that study is presented in Ross and others (2012).

Figure 20—A laser scanner used to scan a historic covered bridge.

Use of Drones for Timber Inspection

Drones with high quality onboard optics have become more affordable, making the use of drones for inspection more viable. Drone inspection has advantages over conventional visual inspection including safety of the inspector and less need for bucket trucks and lifts. Seo and others (2018) examined the use of drones for inspection of masonry and timber structures. Based on a side-by-side comparison of a drone inspection and a visual inspection of the Keystone Wye timber arch bridge in South Dakota, USA, the ability of drones to effectively identify a variety of damage types including cracking, spalling, and corrosion was demonstrated. Seven drone operating features were identified that support structure inspection. They include

1) flying time more than 20 min (longer battery life allows for more efficient inspections),
2) additional camera on top of drone (a top-mounted camera allows for inspection of the underside of structures such as bridges and utility pole cross arms),
3) camera resolution even with low illumination (small defects are more difficult to detect in low illumination due to image quality reduction),
4) high-resolution video (damage detail can more easily be detected with high resolution),
5) adequate payload capacity (for some inspections, additional lights, cameras, or equipment may be needed; a drone capable of carrying additional payload allows for modifications),
6) drone lights (lights mounted to the drone provide extra illumination of dark areas and allow for higher resolution pictures and video), and
7) remote range (some structures to be inspected are distant from safe pilot locations; drones with long ranges provide greater access to remote structures).

Several limitations of drone inspection were also identified. They include

1) high winds can make controlling the drone difficult,
2) intense illumination can cause images to be overexposed, resulting in loss of detail,
3) manual inspection procedures, such as sounding or probing, cannot be performed by a drone,
4) maneuvering in enclosed spaces is difficult for a drone,
5) local DOT may have regulations limiting the use of drones, and
6) Federal Aviation Administration (FAA) regulations limit the operation of drones in some instances (the FAA requires a commercial drone pilot's license when a drone is used for commercial purposes).

Record Keeping

The keeping of inspection records is critical to mat service life and access–right of way systems. In addition to keeping records of installations, inspections, remedial treatments, etc., one can often build up information regarding more troublesome local areas for decay (low lying or swampy areas), where wildlife interactions may be problematic, issues with right of way maintenance (trees and limbs falling), etc. With good inspection and record keeping, the service life of wood mats can be reasonably and safely extended, often into the 6- to 10-year range or more, particularly for mats used in colder climates. Capacity growth in energy, transportation, and other infrastructure continues to build demand for mats. As environmental protection demands increase, the need for mat record keeping and performance metrics also increases.

Concluding Comments

This report provides a summary of important information regarding inspection and assessment of the condition of wood-based mats. It provides a summary of important mechanical properties of wood and the effect that various biological agents have on wood performance. It also provides a review of basic techniques that can be used for condition assessment of wooden construction mats and examines the current state of the art for in-field inspection techniques for wood.

Inspection techniques, and corresponding tools for wood inspection, have advanced considerably in the past 20 years. A wide range of technologies are now available for inspections and are used around the world. Some of these techniques could improve both the service life and safety of wood-based mats.

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